

DESIGN OF HELICOPTER ROTORS TO NOISE CONSTRAINTS

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SUMMARY

Results from the initial phase of a research contract, "Study of Design Constraints on Helicopter Noise," NAS1-15226, sponsored by the NASA Langley Research Center are presented. A description of the overall program is included. Basic calculations of nonimpulsive rotor harmonic and broadband hover noise spectra, over a wide range of rotor design variables were accomplished; and the sensitivity of PNL to changes in rotor design parameters are presented. Measured rotor noise data were used to correlate the calculations in verifying the prediction methodology.

INTRODUCTION

Increased emphasis on reducing the noise generated by helicopter rotors to minimize aural detection times in military applications, and increase community acceptance during commercial operations, now require the helicopter manufacturer to consider noise constraints of his product early in the design phase. Impending noise regulations, such as the FAA/ICAO possible noise limits for certification of helicopters, are forcing designers to implement noise control measures during preliminary design performance studies when the sizing of rotors is being determined.

Basic rotor design parameters such as total thrust, blade tip speed, disk loading, number of blades per rotor, and rotor solidity, which invariably affect the noise produced by the rotor, have generally been decided long before noise restrictions are considered. One reason is that most preliminary designers do not have simplified guidelines for predicting rotor noise which can be meaningful during early rotor design decisions stages. Consequently, most designs are semi-finalized, before noise estimates of the configuration can be made. Subsequent changes that may be required in reducing the noise to comply with certain regulations find themselves in conflict with designs that have already been set.

This study, when completed, will result in a general method, and sets of design charts, which will permit evaluations of the noise and performance tradeoffs of single rotors during the early design stage. The measure of performance will be the percentage of available rotor thrust which must be expended in lifting the drive system (rotor blades, hub, and rotor transmission).

Given a desired thrust and noise limit, the charts can be used to define the corresponding radius, chord, and tip speed for 2, 3, 4, 5 or 6 bladed rotors. The rotor which requires the lowest drive system weight is the optimum design. Conversely, given a completely defined rotor the charts can be used to predict the noise.

Results from the completed initial phase of the study, which includes the calculation of both rotor harmonic and broadband, nonimpulsive hover noise and the relative importance of various rotor design parameters that influence changes in Perceived Noise Level (PNL) are discussed in this paper. 3

SYMBOLS AND ABBREVIATIONS

Values are given in both SI and U.S. Customary Units. The calculations were made in U.S. Customary Units.

T	thrust, N (lb)
V_T	blade tip speed, m/sec (ft/sec)
f_p	peak frequency, Hz
A_b	blade area, m^2 (ft^2)
σ	angle between centerline of rotor shaft and line to observer, deg
S_j	one-third octave frequency band correction
C_L	lift coefficient
r	distance to observer, m (ft)
SPL	Sound Pressure Level, dB (re 2×10^{-5} N/m ²)
PNL	Perceived Noise Level, in PNdB
dBA	A-weighted network
dB(C)	C-weighted network
BB	Broadband noise
PNLT	Tone-corrected Perceived Noise Level
NOY	Unit used in the calculation of Perceived Noise Level. It is the noisiness of a noise for which the Perceived Noise Level is 40 PNdB. The noisiness of a noise that is judged by a subject to be n times that of a 1-NOY noise is n NOYS.

PROGRAM

The objective of the program is to provide a "handbook" for helicopter designers and configuration managers to evaluate the noise of rotors during the preliminary design phase, and to estimate the effect on rotor payload.

In order to produce an effective designer's tool that can be used during noise and performance tradeoff evaluations, the total rotor noise signature has to be represented accurately. All major sources of rotor noise are included in developing the design charts for the handbook. Figure 1 shows an example of these sources and their contribution to the overall noise signature. The subjective weighting of these noise sources; harmonic, broadband (nonharmonic), and impulsive, which is the prelude to determining the PNL, are shown in Figure 2 as total NOY values per octave band. The engine noise minor contribution is shown for completeness only. Examination of this figure indicates that in terms of annoyance, rotor impulse is the major factor; but if the rotor did not have an impulsive characteristic then broadband noise predominates the Perceived Noise Level (Figure 2) to a much greater extent than the Sound Pressure Level Spectrum (Figure 1).

The overall study consists of the following phases:

1. Calculating the nonimpulsive rotor harmonic and broadband noise spectra using established prediction procedures recognized and used by industry and found in open literature. The range of rotor physical parameters included in the calculations are: thrust, 44 to 356 kN (10 000 to 80 000 lb); disk loading, 287 to 575 N/m² (6 to 12 lb/ft²); solidity, 0.04 to 0.12; number of blades, 2 to 6; and tip speed, 152 to 244 m/sec (500 to 800 ft/sec). Calculations are for a sideline distance of 150 meters from rotor and a height of 150 meters (which corresponds to the measurement locations being considered in the regulations). Combining the noise signatures into one-third octave frequency bands calculating PNL, dBA and dBC.
2. Applying impulsive corrections developed by the Boeing Vertol Co. and subjective adjustments from Reference 1 to adjust dBA, dBC and PNL values to a subjectively equivalent broadband level.
3. Preparing a set of design charts to permit direct determination of values of dBA, dBC and PNdB for range of rotor physical parameters. An example of a possible design chart format is shown in Figure 3 for determining the PNdB in hover and, providing a rationale showing the effects of rotor configuration on forward flight noise.
4. Evaluating the performance penalty for each main rotor configuration and tip speed combination. The ratio of drive system weight to rotor thrust shall be used as an index of the design efficiency.

RESULTS AND DISCUSSION

Prediction of Nonimpulsive Rotor Hover Noise

The harmonic rotation noise calculation was based on the method developed in Reference 2. This widely accepted rotor noise calculation includes the design variables of thrust, disk loading, tip speed, and number of rotor blades. The only change made to the equations of Reference 1 was that an airloads harmonic decay exponent of 1.3 was used instead of 2.0, as specified by the original authors. This modification reflects a more realistic airload harmonic decay of 15 dB per octave which has been measured by other researchers and provides better agreement with measured data in the higher harmonic range.

The broadband, or nonharmonic, rotor noise calculation used was from the unpublished semiempirical prediction made by Robert J. Pegg of the NASA Langley Research Center. The equation from this prediction,

$$\begin{aligned}f_p &= -240 \log T + .746 V_T + 786 \\SPL &= 10 \log A_b + 60 \log V_T + 10 \log (\cos^2 \sigma + .1) \\&\quad + S_j - 20 \log r + f(C_L) - 53.29 \\f(C_L) &= 10 \log \frac{\overline{CL}}{.4} \quad \text{for } \overline{CL} \leq .48 \\f(C_L) &= .9 + 80 \log \frac{\overline{CL}}{.48} \quad \text{for } \overline{CL} \geq .48\end{aligned}$$

has as its design variables, thrust (T), tip speed (V_T), blade area (A_b) and lift coefficient (C_L).

A computer program was written to include all of the design variables and to provide an automatic calculation of both the harmonic and broadband noise, then combine them into one-third octave frequency bands and print-out the resultant dBA, dBC and PNL. Figure 4 shows a sample of this output. Nine hundred sixty computer cases were run during the initial phase of the program to provide adequate definition of the design variables for preparation of the "handbook" charts.

Prediction-Data Correlation

Measured noise data, shown in Figures 5 and 6, from a nonimpulsive and moderately impulsive rotor were directly compared to the calculated one-third octave SPL using the developed computer program. The agreement between predictions and measurement for the nonimpulsive case (fig. 5) are generally quite good, the discrepancy in the 500 Hz octave band is probably due to destructive interference between the direct and first ground reflected waves which calculates to occur at 556 Hz. In the case of the impulsive rotor (fig. 6) good agreement is attained in the first two harmonics and higher frequency broadband noise since the harmonic noise prediction method does not account for the increase in mid-harmonic loading which typifies impulsive rotor noise.

Perceived Noise Level Sensitivity to Rotor Design

To provide an indication of the sensitivity of PNL to changes in design variations, five baseline rotor designs representing different classes of helicopters were investigated. For each baseline configuration the rotor parameters of thrust, disc loading, tip speed and number of blades were varied one at a time (at constant lift coefficient) and the resultant PNdB calculated.

Figure 7 shows an example of the calculated nonimpulsive hover SPL for one particular case (3-bladed, 89-kN (20 000-lb) thrust rotor). Taking this configuration as a baseline design and varying each of the parameters one at a time results in the PNL sensitivity chart shown in figure 8. Similar studies have been done for four other baseline designs which cover a wide range of values and the resultant summary (table I) indicates some rough guidelines which can be used pending release of the final design charts which will result from this study.

CONCLUDING REMARKS

The calculation of the nonimpulsive harmonic and broadband hover noise for a wide range of rotor design variations was accomplished. The prediction methodology used correlated well with measured whirl tower data. Application of the predictions to variations in rotor design (thrust, tip speed, disc loading, and number of blades per rotor) has shown tip speed and thrust as having the most effect on changing the PNL.

REFERENCES

1. Sternfeld, Harry, Jr.; and Doyle, Linda Bukowski: Evaluation of the Annoyance Due to Helicopter Rotor Noise. NASA CR-3001, 1978.
2. Lowson, M.V.; and Ollerhead, J.B.: Studies of Helicopter Rotor Noise. USAAVLABS Tech. Rep. 68-60, U.S. Army, Jan. 1969.

TABLE I.- INTERIM RESULTS SUMMARY OF SENSITIVITY OF PNL
TO DESIGN PARAMETER VARIATION

Parameter	Range	Sensitivity*
Tip speed	137 to 290 m/sec (450 to 950 ft/sec)	2 to 5 PNdB per 30.5 m/sec (100 ft/sec)
Thrust	11 121 to 358 876 N (2 500 to 80 000 lb)	2 PNdB per doubling of thrust
Disk loading	96.1 to 574.6 N/m ² (2 to 12 lb/ft ²)	0.5 PNdB per 96.1 N/m ² (2 lb/ft ²)
Number of blades per rotor	2 to 6	<0.5 PNdB per blade addition

*Based on varying parameter under study while holding all others constant.

ALTITUDE 120 m (394 ft)

GROSS WEIGHT 18 140 kg
(40,000 lb)

TIP SPEED 234 m/sec
(769 ft/sec)

AIRSPEED 111 km/hr
(69 mi/hr)

SOUND PRESSURE
LEVEL — dB RE
2 X 10⁻⁵ N/m²

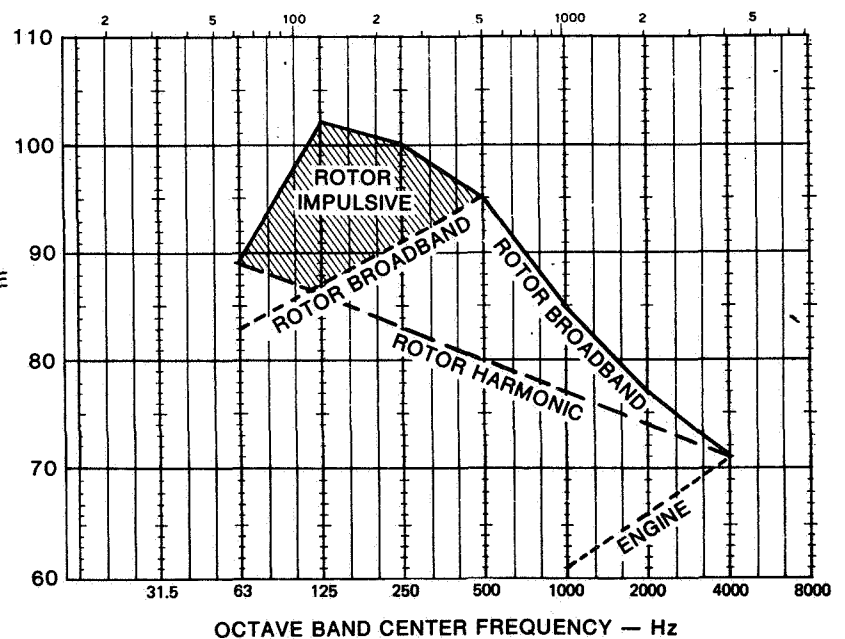


Figure 1.- Helicopter noise source contribution during 6-degree approach.

ALTITUDE 120 m (394 ft)
 GROSS WEIGHT 18 140 kg
 (40,000 lb)
 TIP SPEED 234 m/sec
 (769 ft/sec)
 AIRSPEED 111 km/hr
 (69 mi/hr)
 PNL - 107 PNdB

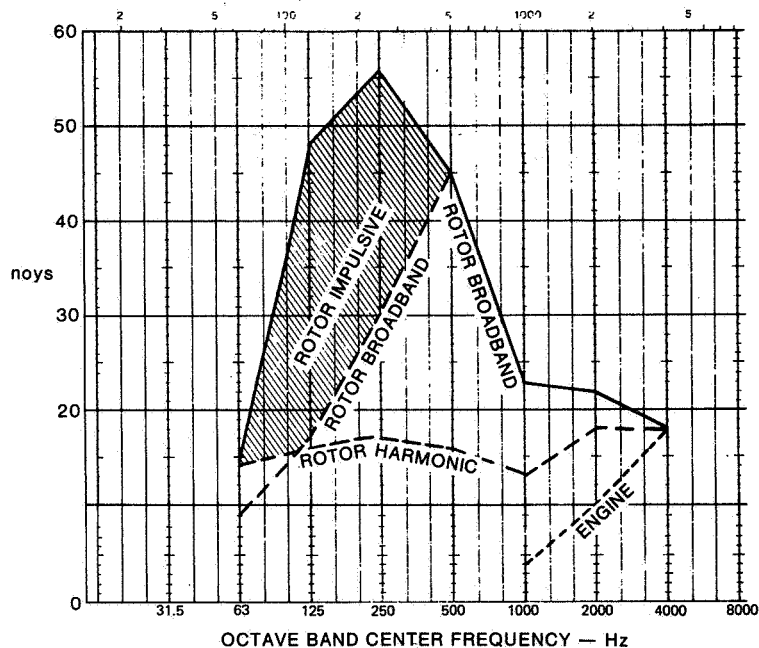


Figure 2.- Subjective weighting of helicopter noise during 6-degree approach.

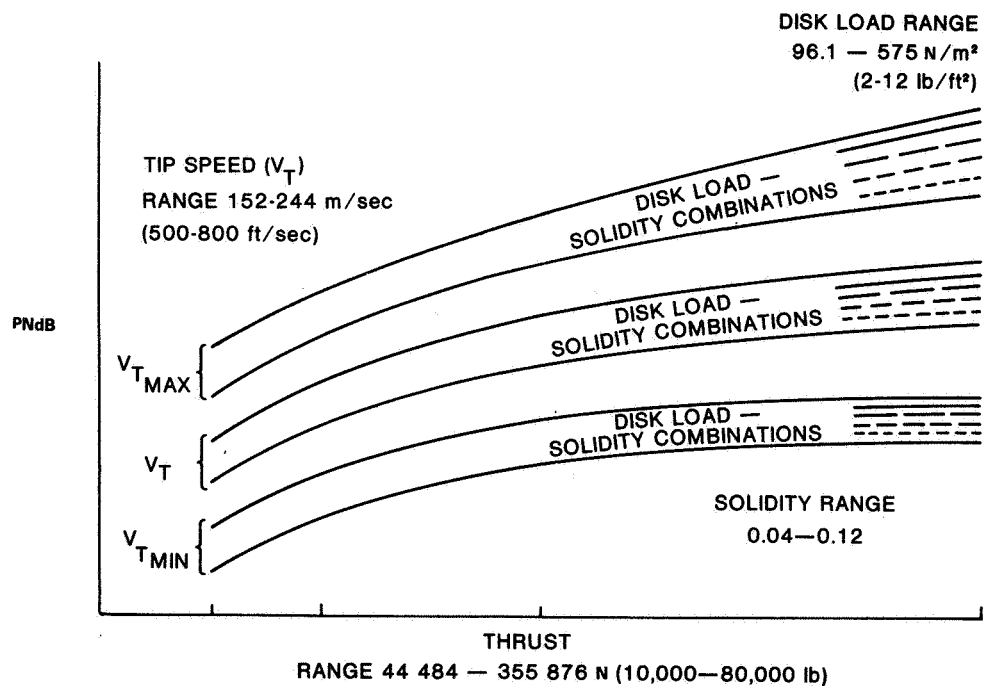


Figure 3.- Possible design chart format for 2-, 3-, 4-, 5-, and 6-bladed rotors.

***** * KASE 5141 * *****								
INPUT DATA								
ROTOR THRUST 15000.	ROTOR TIP SPEED 750.	ROTOR SOLIDITY +1000	DISC LOAD R+00	NUM BLADES 4	KNHITS 0.	BB EFFECT. TIP SPEED 750.	HARMONIC FUND.FREQ 19.5%	
BLADE RADIUS 24.4	ROTOR RPM 293.2	TIP MACH NO. +671	ROTATION MACH NO. +537	FLIGHT MACH NO. +000	EFFECT. MACH NO. +537	LIFT COEFF. +359	PEAK BB FREQ. 343.2	PEAK BB SPL 70.4
BB DBA 75.7	BB DBC 78.9	HARMONIC DBA 70.7		HARMONIC DBC 84.9		TOTAL DBA 76.9	TOTAL DBC 85.9	

A

***** BROAD-BAND NOISE *****			***** ROTATIONAL NOISE *****				***** TOTAL NOISE *****		
FREQ BAND	FREQ	SPL	HARMONIC	FREQ	SPL	FREQ BAND	SPL	FREQ BAND	SPL
****	*****	*****	*****	*****	*****	****	*****	****	*****
20	21.5	53.4	1	19.5	87.1	20	87.1	20	87.1
25	27.0	55.1	2	39.1	80.7	25	80.7	25	80.7
31	34.1	56.7	3	58.6	75.6	31	75.6	31	75.6
40	42.3	58.4	4	78.2	72.7	40	72.7	40	72.7
50	54.1	59.8	5	97.7	70.9	50	70.9	50	70.9
63	68.1	61.2	6	117.3	69.4	63	69.4	63	69.4
80	85.8	62.6	7	136.7	68.3	80	68.3	80	68.3
100	108.1	63.8	8	156.4	67.3	100	67.3	100	67.3
125	136.2	65.0	9	175.9	66.4	125	66.4	125	66.4
160	171.6	66.2	10	195.4	65.6	160	65.6	160	65.6
200	216.2	67.6	11	215.0	64.9	200	64.9	200	64.9
250	272.4	69.0	12	234.5	64.3	250	64.3	250	64.3
315	343.2	70.4	13	254.1	63.7	315	63.7	315	63.7
400	429.5	71.7	14	273.6	63.2	400	63.2	400	63.2
500	544.9	72.4	15	293.2	62.6	500	62.6	500	62.6
630	686.5	73.1	16	312.7	62.2	630	62.2	630	62.2
800	864.9	73.8	17	332.2	61.7	800	61.7	800	61.7
1000	1080.7	74.5	18	351.8	61.3	1000	61.3	1000	61.3
1250	1473.0	75.2	19	371.3	60.9	1250	60.9	1250	60.9
1600	1929.8	75.9	20	390.9	60.6	1600	60.6	1600	60.6
2000	2479.4	76.6	21	410.4	60.2	2000	60.2	2000	60.2
2500	3146.0	77.3	22	430.0	59.9	2500	59.9	2500	59.9
3150	4059.6	78.0	23	449.5	59.5	3150	59.5	3150	59.5
4000	5258.8	78.7	24	469.1	59.2	4000	59.2	4000	59.2
5000	6819.8	79.4	25	488.6	58.9	5000	58.9	5000	58.9
6300	8919.3	80.1	26	508.1	58.7	6300	58.7	6300	58.7
8000	11717.7	80.8	27	527.7	58.4	8000	58.4	8000	58.4
10000	15483.6	81.5	28	547.2	58.1	10000	58.1	10000	58.1
			29	566.8	57.9				
			30	586.3	57.6				
			31	605.9	57.4				
			32	625.4	57.2				
			33	645.0	56.9				
			34	664.5	56.7				
			35	684.0	56.5				
			36	703.6	56.3				
			37	723.1	56.1				
			38	742.7	55.9				
			39	762.2	55.7				
			40	781.8	55.6				

B

Figure 4.- Rotor noise calculation - computer program sample output.


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***** COMBINED BROADBAND AND HARMONIC PERCEIVED NOISE DATA *****
FREQENCY = HZ      LEVEL = DB      NOYS      CORRECTION
50      59.8      4.57      .00
63      75.8      4.36      1.55
80      73.1      4.27      .00
100     71.6      4.86      .00
125     72.7      5.85      .00
160     71.4      6.03      .00
200     70.9      6.79      .00
250     71.7      7.75      .00
315     72.4      8.79      .00
400     71.0      8.55      .00
500     70.2      8.10      .00
630     69.3      7.60      .00
800     57.5      5.74      .00
1000    66.0      6.05      .00
1250    65.8      6.85      .00
1600    64.3      8.04      .00
2000    62.9      8.41      .00
2500    61.2      8.58      .00
3150    61.1      9.13      .00
4000    60.9      9.01      .00
5000    59.4      7.53      .00
6300    57.9      6.38      .00
8000    56.1      4.58      .00
10000   54.6      3.36      .00

PALT = 91.3
PAL = 83.8
CORRECTION = 1.55

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C

Figure 4.- Concluded.

ROTOR THRUST 66,727 N
 (15,000 lb)
 ROTOR TIP SPEED 229 m/sec
 (750 ft/sec)
 ROTOR SOLIDITY 0.1
 DISK LOAD 303 N/m²
 (8 lb/ft²)
 BLADE RADIUS 7.5m
 (24.5 ft)

SOUND
 PRESSURE
 LEVEL — dB RE
 $2 \times 10^{-5} \text{ N/m}^2$

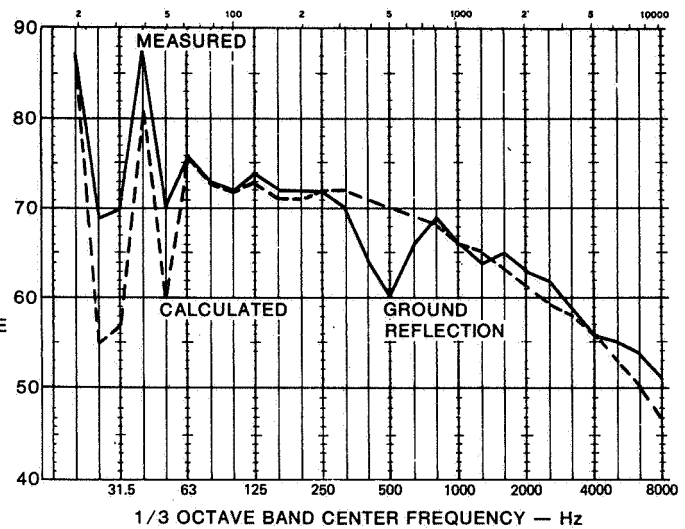


Figure 5.- Correlation of calculations with whirl tower nonimpulsive rotor noise at 152-m (500-ft) distance.

ROTOR THRUST 266,907 N
 (60,000 lb)
 ROTOR TIP SPEED 229 m/sec
 (750 ft/sec)
 ROTOR SOLIDITY 0.09
 DISK LOAD 430 N/m²
 (9 lb/ft²)
 BLADE RADIUS 14m (46 ft)

SOUND PRESSURE
 LEVEL — dB RE
 $2 \times 10^{-5} \text{ N/m}^2$

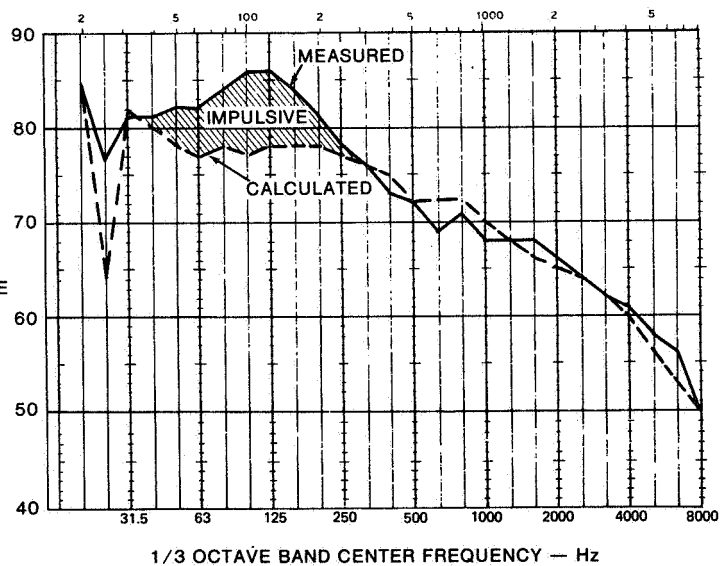


Figure 6.- Correlation of calculations with whirl tower impulsive rotor noise at 152-m (500-ft) distance.

BASE POINT VALUES

THRUST 88,969 N
(20,000 lb)

TIP SPEED 229 m/sec
(750 ft/sec)

DISK LOADING 287 N/m²
(6 lb/ft²)

SOLIDITY 0.06

LIFT COEFF 0.449

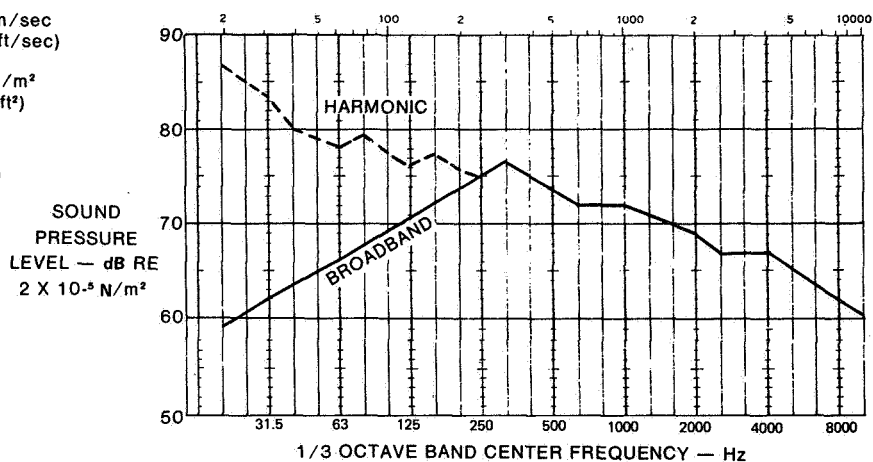


Figure 7.- Calculated - nonimpulsive hover noise 3-bladed rotor at 152-m (500-ft) distance.

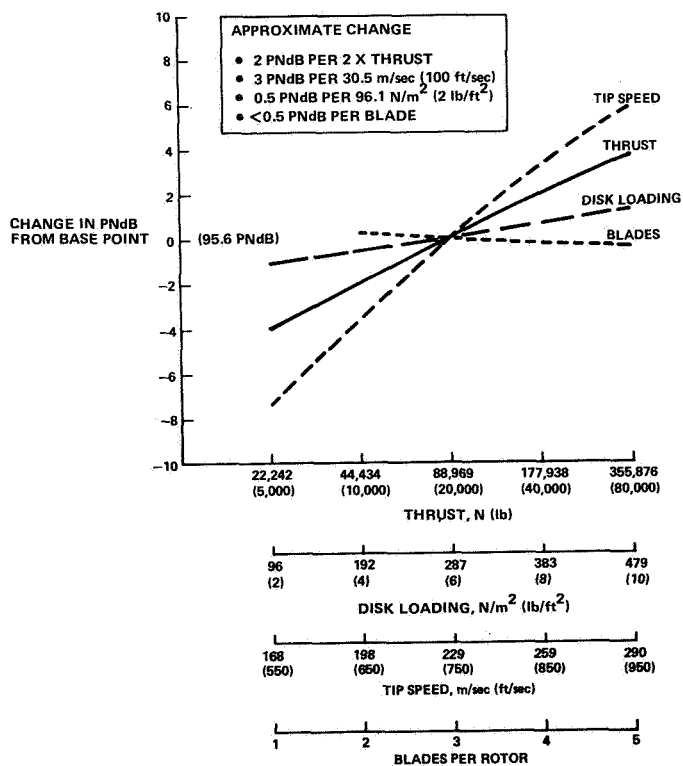


Figure 8.- Relative change in PNdB with design parameter variation.